THE CHANGE RATE OF FUEL CONSUMPTION FOR DIFFERENT IRI OF PAVED ROADS

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ABSTRACT

High VOC(Vehicle Operating Cost) is the main reason for the rehabilitation of paved road. And VOC is composed of fuel consumption, lubricant oil consumption, parts consumption, etc. Therefore it's important to calculate or measure fuel consumption for various road conditions for the fuel consumption is one of the largest components of VOC.

In this study, the fuel consumption is measured on two paved roads of different IRI(International Roughness Index) and various speeds. The change rate of fuel consumption for different IRI and speed was measured with the results of this test. The fuel consumption was measured by processing the voltage signal of fuel injector of vehicle and the speed was measured with GPS.

It's concluded that fuel consumption(L/100km) of medium and large car increases 7 times fast of the increase of IRI around 3.5m/km in the speed range of 40 ~ 100km/h, and fuel consumption is best at 60km/h in the paved road of around 3.5m/km IRI level in this study.

1. INTRODUCTION

VOC(Vehicle Operating Cost) includes fuel consumption, tire consumption, oil consumption and various parts consumption. The fuel consumption is the one of the highest terms of VOC and this VOC changes with the various conditions of road(surface roughness, gradient, curve radius and weather, etc). The fuel economy is expressed in the number of kilometers can be driven with 1 liter of fuel, and VOC is assumed to increase as the fuel economy deteriorates. The road surface roughness is the key criterion for the road rehabilitation among these road conditions because gradient, curve

radius, weather condition are the geographical conditions, on the other hand surface roughness indicates the level of deterioration of the road. Therefore we can say that the road should be rehabilitated because of the high VOC when the fuel consumption is high and this fuel consumption is influenced by the road surface roughness directly. But this important change rate of fuel consumption with the road surface roughness is not measured in Korea yet. Of course this change rate is calculated with HDM-4(Highway Development & Management) computing program in Korea as many other countries, but the conditions of road and vehicle can be different from the ones of the countries developed HDM-4.

So we measured the change rate of fuel consumption for the road surface roughness and various speeds of Korean vehicles in this study. We can determine to rehabilitate the road or not for various road surface roughness with the results of this study. And we can compare the measured fuel consumption results with the calculated ones of HDM-4 afterwards.

2. TEST CONDITIONS

2-1 Test Vehicle Selection

The HDM-4 is accepted worldwide to calculate VOC and determine investment or rehabilitation for roads. VOC is calculated with the variables like vehicle type, operating speed and road type, etc in HDM-4. We selected the test vehicles with the standard of HDM-4 used for calculation of VOC in Korea. And we measured the fuel consumption of the selected Korean vehicles for different speed and road.

Vehicle Number	Type	Description
1	Motorcycle	Motorcycle or scooter
2	Small car	Small passenger cars
3	Medium car	Medium passenger cars
4	Large car	Large passenger cars
5	Light delivery vehicle	Panel van, utility or pickup truck
6	Light goods vehicle	Very light truck for carrying goods (4 tyres)
7	Four wheel drive	Landrover/Jeep type vehicle
8	Light truck	Small two-axle rigid truck (approx. < 3.5 t)
9	Medium truck	Medium two-axle rigid truck (> 3.5 t)
10	Heavy truck	Multi-axle rigid truck
11	Articulated truck	Articulated truck or truck with drawbar trailer
12	Mini-bus	Small bus based on panel van chassis (usually 4 tyres)
13	Light bus	Light bus (approx. < 3.5 t)
14	Medium bus	Medium bus (3.5 - 8.0 t)
15	Heavy bus	Multi-axle or large two-axle bus
16	Coach	Large bus designed for long

Figure 1. Vehicle type of HDM-4

There are three types of passenger cars in HDM-4 as shown in Figure 1, and these three types are small, medium and large car. The operating weight is about 1.0 ton for small car, 1.2 ton for medium car and 1.4 ton for large car each. So it's medium car if engine displacement is about 2000cc and large car if it's about 3000cc for Korean vehicles.[1]

We selected test vehicles which have highest market share in Korea, namely NF Sonata for medium car and Grandure TG for large car. These test vehicles can represent the same class of Korean vehicles and it's suitable for the characteristics of HDM-4 calculating average operating cost of whole vehicles passing the specific roads. The specifications of these two cars are shown in Figure 2.

Spec.	NF Sonata	Grandure TG
Model Year	2007	2006
Mileage	60,000km	80,000km
Transmission	Automatic	Automatic
Gross weight	1795kg	2014kg
Engine displacement	1998cc	3342cc
No. of cylinder	4	6
Power/RPM	144PS/6000RPM	233PS/6000RPM
Fuel	Gasoline	Gasoline
Certified Fuel Economy	10.8km/L	9.0km/L
Picture		

Figure 2. The specifications of test vehicles

2-2. Test speed selection

The VOC is calculated with characteristic speeds of each vehicle type in HDM-4 as shown in figure 3, and the characteristic speed is free speed(S1~S3), operating speed(S3~Snom) and congested speed(Snom~Sult). The free speed is a vehicle speed

when the traffic volume is small and this speed is limited by traffic regulation, engine power or safety(like braking power in declined road). The operating speed is a limited speed by other passing cars, pedestrians or traffic signal when the traffic volume increases. And the congested speed is a limited speed by extremely large traffic volume.

The average vehicle speed is calculated by relating these characteristic speeds with traffic volume for the road. So the average vehicle operating speed varies with vehicle and road types and traffic volume. The test speed was at 4 points from 40 to 100km/h with increase of 20km/h(i.e. 40, 60, 80, 100km/h) in this study, so that the test results can be used for various vehicle and road types.

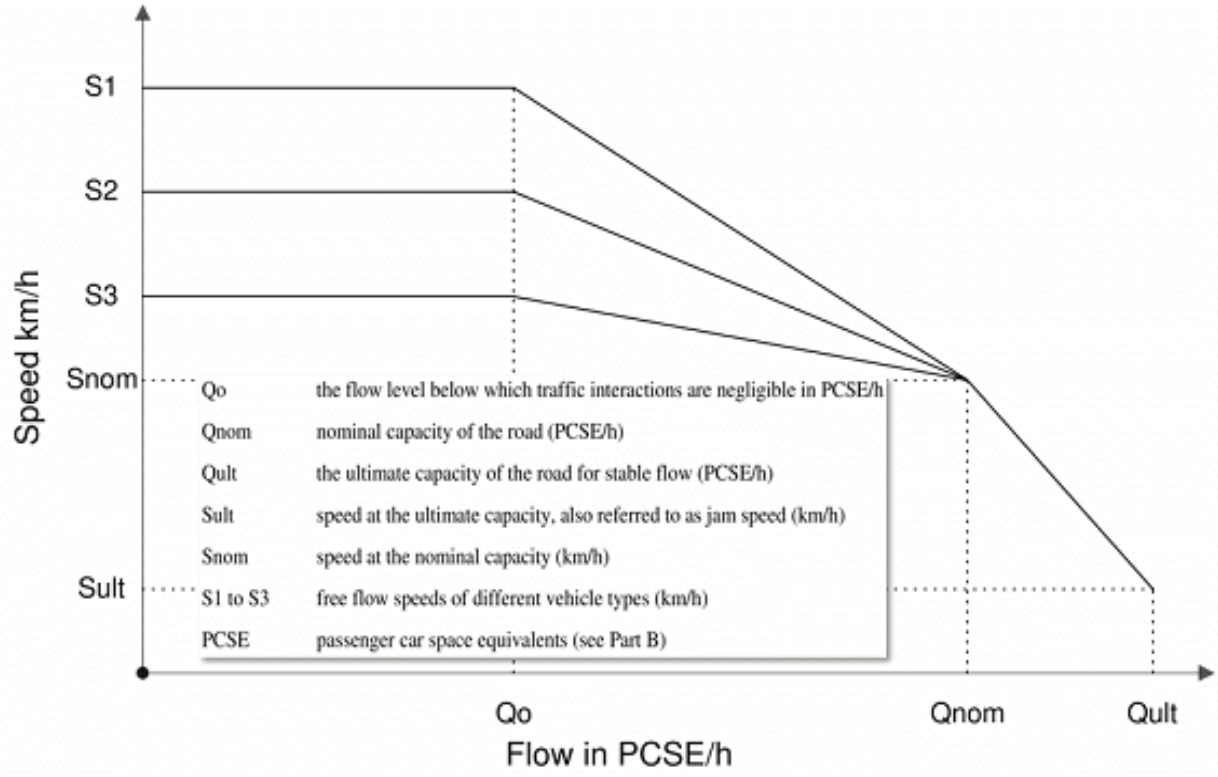


Figure 3. The Characteristic speed in HDM-4

2-3. Test roads

It's important to measure precise conditions of road because the goal of this study is to understand the relation of fuel consumption and road conditions. The conditions of roads differ with the materials of pavement and are composed of surface roughness, gradient, curve radius, dryness, width, number of lanes and etc. in HDM-4.

Among these conditions surface roughness is a key characteristic representing road deterioration because other conditions are geographical conditions. Therefore other conditions but surface roughness are excluded in this study. The fuel consumption was

measured for constant speed in a straight level road and by averaging fuel consumption for rounding trip to eliminate the direction of wind and gradient of road. [2], [3]

This study should be performed in straight and level road to eliminate the effect of gradient and curve radius of road. And the traffic volume should be small because the test speed is from very low speed(40km/h) to high speed(100km/h) and the speed should be constant during the measurement of fuel consumption of each round trip.

We selected 2 sections of roads satisfying above conditions(straight and level road with small traffic volume) for this measurement. One is a side road of sea wall in Nampo, and the other is also a side road of sea wall in Sukmun. And these two roads are in Chungnam, South Korea. Both of these two roads are typical country road in Korea which have two lanes and very small traffic volume. The length of these roads is about 3km for round trip. The pictures of these test roads are shown Figure 4.

Nampo(North to South)	Nampo(South to North)
	
Sukmun(North to South)	Sukmun(South to North)
	

Figure 4. Test Roads

2-4. Measurement of fuel economy

It's necessary to measure fuel consumption and driven distance for calculation of fuel economy. The fuel consumption was measured by using the electronic control method of injectors of gasoline engine. There are two wires for each injector as shown in figure 5.

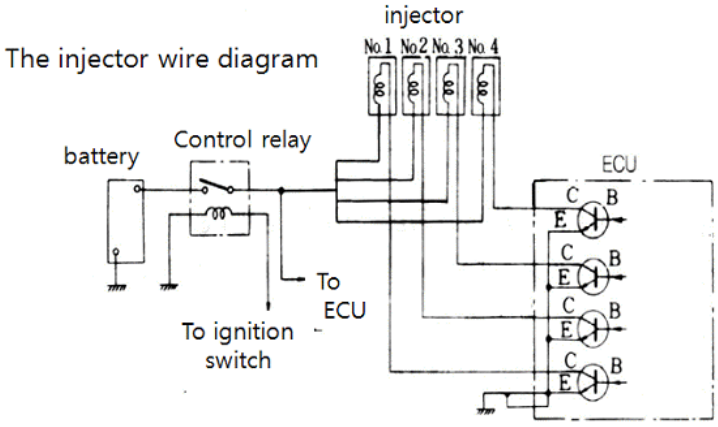


Figure 5. The injector wire diagram

One is for supplying electricity to injector from battery and the other is connected to ECU(Engine control unit). The injector is open when the wire connected to ECU is set to ground, i.e, zero voltage by ECU. In other words, injectors spray fuel when the voltage of wire connected to ECU is zero as shown figure 6.

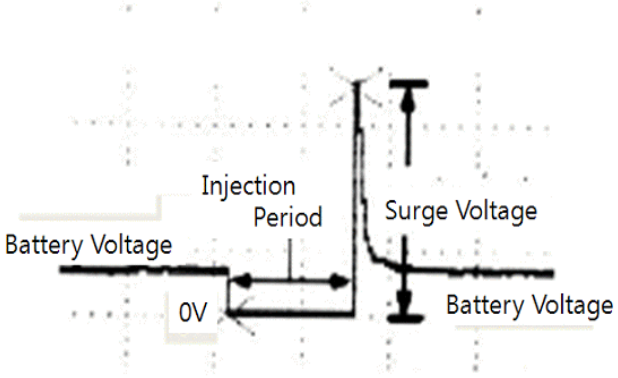


Figure 6. The electric signal of injector

And the amount of injected fuel is proportionate to the length of this zero voltage period. Therefore we can compute the injected fuel by measuring the time period of zero voltage of this wire connected to ECU. The fuel consumption is calculated as formula (1).

The amount of injected fuel[mcc] = Correction factor X Injection period[ms] ----------(1)

We could fix the correction factor by measuring vehicle weight difference after driving the vehicle about 400km because the weight difference is due to the fuel consumption. By this method we can measure the fuel consumption without direct measuring fuel flow rate in and out from fuel pump which varies with fuel temperature. The work of connecting hose to/from fuel pump is very cumbersome and the flow meter is very expensive. We can avoid these problems by measuring just voltage signal of injectors. The driven mileage was measured by GPS sensor. As explained earlier we can calculate the fuel economy with these two data, i.e., fuel consumption and driven distance. And the road surface roughness was measured as IRI(International Roughness Index).[4]

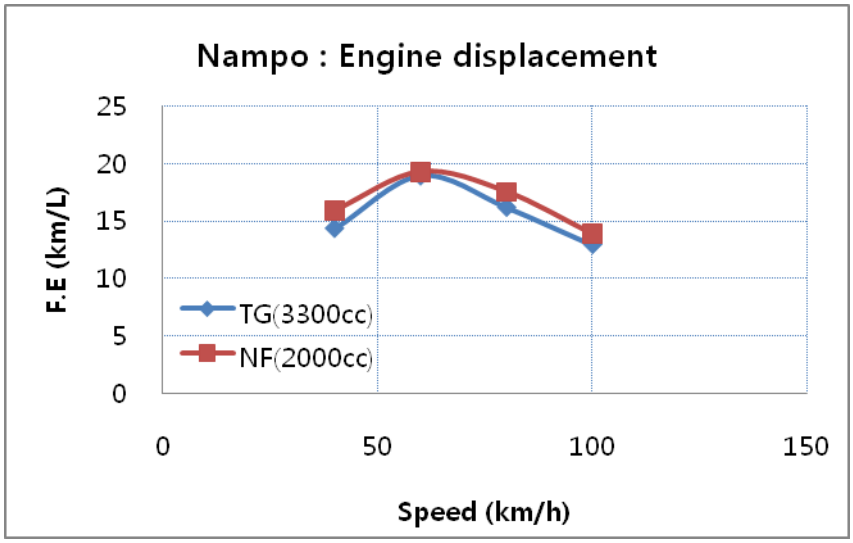
3. TEST RESULTS

3-1. Fuel economy by engine displacement

Test results of Nampo and Sukmun seawall side road is summarized in Table 1 and Figure 7. The fuel economy is the best at speed of 60km/h for both engine displacement of 2,000cc and 3,300cc as about 18~19km/L in this study. And the maximum speed of traffic regulation for these two roads is 60km/h. Therefore it's good in the view of fuel economy's point when the traffic volume is small and the vehicle can speed up to the highest speed of traffic regulation at 60km/h which is the best for fuel economy. As the traffic volume grows, the speed will be slow down and then the fuel economy becomes bad. The fuel economy gets bad a little as the engine displacement becomes larger as expected.

Table 1. Test results of each road

Road	Speed (km/h)	IRI (m/km)	Fuel Economy(km/L)	
			TG(3,300cc)	NF(2,000cc)
Nampo	40	***3.56***	14.34	15.97
	60		18.92	19.33
	80		16.18	17.59
	100		12.93	13.92
	Average		***15.59***	***16.70***
Sukmun	40	***3.59***	13.62	15.62
	60		18.44	18.92
	80		15.87	16.05
	100		12.73	13.78
	Average		***15.16***	***16.09***



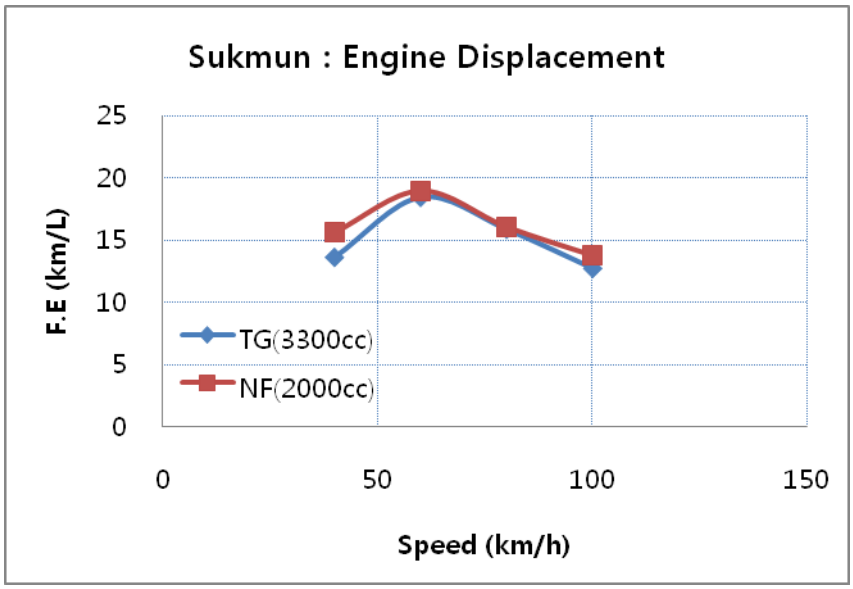


Figure 7. Fuel economy with engine displacement

3-2. Fuel economy by surface roughness

The road surface roughness was measured as IRI(International Roughness Index), vertical vibration per horizontal driving and its unit is [m/km]. The IRI is 3.56m/km for Nampo, 3.59m/km for Sukmun sea wall side road each. The test results are shown in Table 2 and Figure 8. The fuel consumption per 100km in Table 2 is an average of 2,000cc and 3,300cc test results for 4 points of speeds(40, 60, 80, 100km/h)..

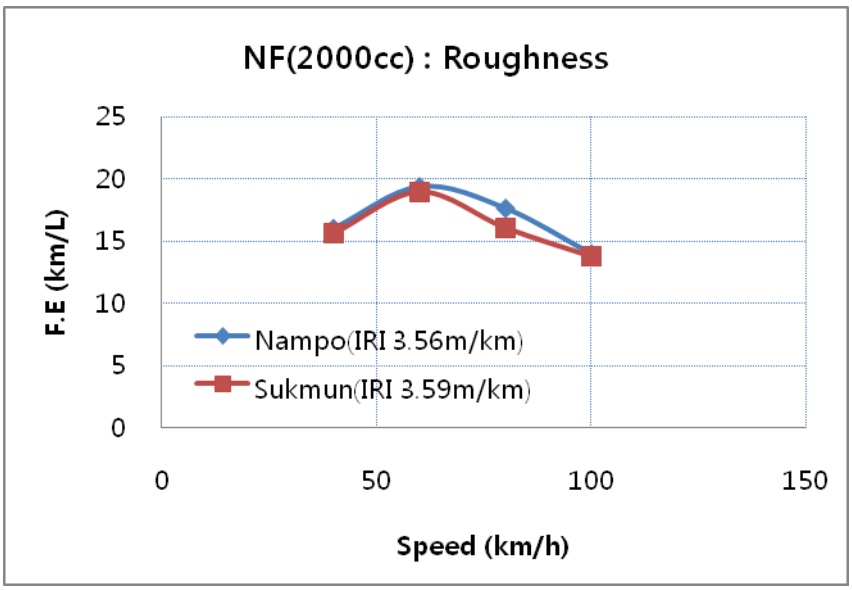
Table 2. Test results of Fuel Economy and IRI

IRI(m/km)	F.E(L/100km)	△FE /△IRI [(L/100km) / (m/km)]
3.56	6.19	-
3.59	6.40	7.0

There is slight deterioration in the fuel economy as IRI increases. The VOC is linearly proportionate to IRI, and the fuel consumption is a large term in VOC. [5] Therefore the fuel consumption can be expressed as 1st order of the IRI in this study as formula (2).

$$FE[L/100km] = a \times IRI[m/km] + b \qquad (2)$$

And the constants,*a* and *b* can be calculated with these test results as *a* = 7.0, *b*=-18.73. This means that fuel consumption per 100km increases 7 times of increase of IRI[m/km]. But this result is calculated with only two data, and the IRIs of the test result are 3.56 and 3.59, which is so close to each other. So we should be careful to apply this results, and the conclusion is that the fuel consumption(L/100km) for medium and large car increases 7 times fast with increasing IRI around 3.5m/km in the speed range of 40 ~ 100km/h. And it's necessary to do more fuel consumption tests for different road surface roughness.



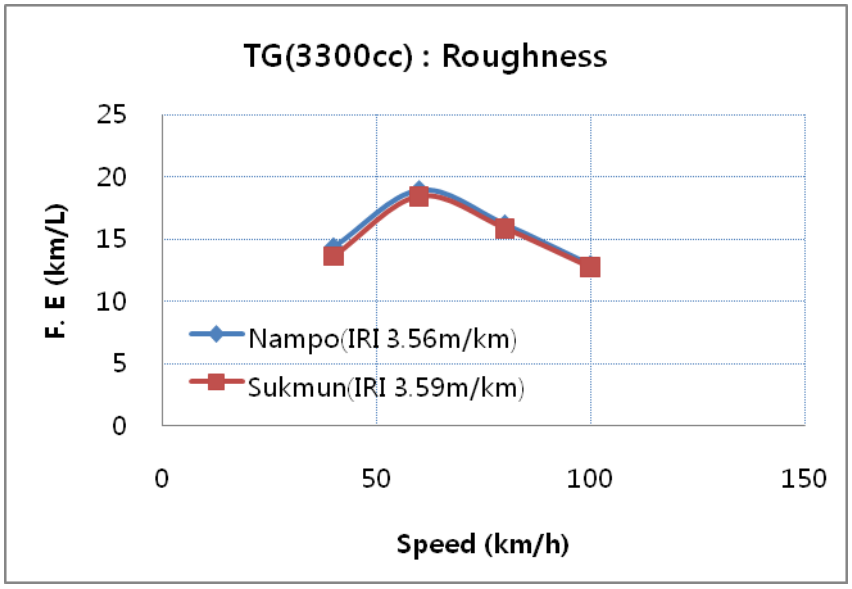


Figure 8. Fuel economy for surface roughness

4. CONCLUSION

Fuel economy was measured for different road surface roughness with medium(2,000cc) and large(3,300cc) car in the speed range of 40~100km/h. The fuel consumption was measured by measuring injection period of injector of vehicle and driven distance by GPS sensor. The IRI of test roads were 3.59 and 3.56m/km.

The fuel economy deteriorates as engine displacement increases and best at 60km/h which is the highest speed of traffic regulation of the test roads.

The fuel consumption(L/100km) is linearly proportionate to IRI(m/km) because VOC($/km) is linearly proportionate to IRI and the fuel consumption is large term in VOC.

The fuel consumption(L/100km) of medium and large car increases 7 times fast of the increase of IRI around 3.5m/km in the speed range of 40 ~ 100km/h.

It's necessary to do more tests for different surface roughness to relate fuel consumption and IRI.

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